Physicochem. Probl. Miner. Process. 52(1), 2016, 328−341

www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received January 27, 2015; reviewed; accepted July 27, 2015

EXPERIMENTAL STUDY ON TRIBOELECTROSTATIC BENEFICIATION OF WET FLY ASH USING MICROWAVE HEATING

Haisheng LI, Yinghua CHEN, Xinxi ZHANG, Yuemin ZHAO, Youjun TAO, Chaoyong LI, Xin HE

Key Laboratory of Coal Processing and Efficient Utilization (Ministry of Education), School of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou 221116, Jiangsu, China, cyhlhs@163.com (H. Li), zhangxinxi@126.com (X. Zhang)

Abstract: Triboelectrostatic beneficiation, as a physical method, of fly ash cannot only meet the technical requirements of fly ash application but also recycle of an unburned carbon as a useful energy source. The aim of this study was to investigate the feasibility of improving efficiency of triboelectrostatic beneficiation of wet fly ash using microwave heating. The wet fly ash with different moisture contents had an average loss-on-ignition of 12.56%. The fly ash samples were heated in a microwave oven before the experiments. The experimental conditions were electric field voltage of 40 kV and air flux ranging from 12 to 30 m^3/h. The influence of the microwave heating on the wet fly ash triboelectrostatic beneficiation was discussed under the conditions of different microwave intensity and irradiation time. The results indicated that the removal rate and recycle rate of the unburned carbon showed a significant increase performance as the wet fly ash was processed by the microwave heating which was attributed to changes of moisture contents and dielectric constants caused by the microwave heating. The feasibility had been verified according to the experimental study on fly ash with different moisture contents. It can be concluded that the microwave heating process was efficiently applied for the wet fly ash triboelectrostatic beneficiation.

Keywords: *wet fly ash, triboelectrostatic beneficiation, microwave heating, efficiency*

Introduction

Fly ash is a solid waste produced by coal-fired power plants, and it can be harmful to the environment because of air pollution, groundwater contamination etc. On the other hand, it is also a sort of useful resource (Hwang et al., 2002) and several researchers have focused on the utilization of fly ash (Soong et al., 2001; Huang et al., 2003). At present, the fly ash has been widely used as a kind of additive for building materials.

http://dx.doi.org/10.5277/ppmp160128

The influence of carbon content on the building materials was proven by some previous studies (Kim et al., 2001; Cangialosi et al., 2010).

Removal unburned carbon from fly ash can be achieved using flotation and electrostatic separations. Flotation is an effective method to remove unburned carbon from fly ash (Cao et al., 2012; Huang et al., 2003). However, the pretreatment technique of flotation needs a lot of water, and the post-processing needs dehydration equipment. Accordingly, the equipment investment and energy consumption should be taken into consideration. The follow-up use of fly ash production obtained by flotation is difficult because of low activity. Moreover, the flotation reagents will cause the environmental pollution. By contrast, the electrostatic separation has an obvious advantage over the flotation. As also known from literature, the triboelectrostatic separation has been studied as a cost-effective solution for fly ash beneficiation (Ban et al., 1997). Therefore, it is suitable to be used especially for the water-deficient area.

Recent two investigations were focused on questions regarding ash triboelectrostatic beneficiation. On one hand, the separation efficiency should be improved to obtain high-quality ash product with low carbon content (Cangialosi et al., 2008). On the other hand, the recovery efficiency of unburned carbon needs to be enhanced with the improvement of their awareness of energy resources (Li et al., 2012). Removal of unburned carbon from wet fly ash is difficult to achieve in a continuous operation at low temperature and high relative humidity. Especially in some southern regions of China, the fly ash collected by a dry method will absorb a bit of moisture during the winter or rainy weather. In some places, the fly ash produced by coal-fired power plants is collected by a wet method. Therefore, humid fly ash is generally processed by a dryer.

The temperature and moisture content has an important effect on the wet fly ash triboelectrostatic beneficiation. The relative humidity and temperature of air flow used to convey fly ash particles have an impact on the electrical charging process. As the particle size decreased, the influence of air humidity and surface moisture would be more important. The particles less than 45 μm had a four-fold change in their separability once changing their surface moisture contents (Cangialosi et al., 2006). An experimental methodology was introduced to measure electrical charge distributions of fly ash particles exposed to weather conditions for six months. It is suggested that removal of surface moisture would be beneficial to improve the efficiency of the fly ash triboelectrostatic beneficiation (Cangialosi et al., 2009). Also, the configuration of tribo-charger and the operational parameters have an important influence on the fly ash triboelectrostatic beneficiation (Li et al., 2015). The temperature field inside the tribo-device can reflect the efficiency of friction and collision indirectly. The tribo-charger was optimized by infrared thermography experiments (Li et al., 2013). A remarkable increase in separation efficiency was obtained after heating fly ash with loss-on-ignition (*LOI*) content below 15%. The adhesive forces between coal and ash caused by moisture adsorption may be a factor influencing triboelectrostatic beneficiation performance for the wet fly ash (Cangialosi et al., 2006).

In general, the heating of mineral particles is utilized in a microwave oven. In recent literature, the mixed oxide powders were prepared by the microwave heating before the experiments (Kato, 2012). Microwave heating of mineral ores offers a mechanism to induce fractures around grain boundaries. The process was influenced by microwave power and thermal expansion coefficient (Ali et al., 2010). The effect of microwave treatment on the processing of mineral ores was investigated through simulations of microwave heating (Ali et al., 2011).

Obviously, the microwave heating would be more efficient than others. The wet fly ash processed by the microwave heating has several technical advantages. Firstly, the microwave heating is uniform and fast. The temperature of particles will rise, and the moisture distribution of their surface will change. Secondly, the charged process has a close relationship with the collision and vibration of the particles caused by the microwave heating. Thirdly, the temperature and moisture contents of particles can be controlled by the adjustable parameters of the microwave heating. Finally, the microwave heating operated in a closed environment will not produce dust pollution. Thus, it could be used as a pre-process for wet fly ash particles during the triboelectrostatic beneficiation. In this context, the aim of this study was to discuss the feasibility of realizing the wet fly ash triboelectrostatic beneficiation efficiently using microwave heating. The experimental results can provide some references for the engineering applications.

Experimental

Materials

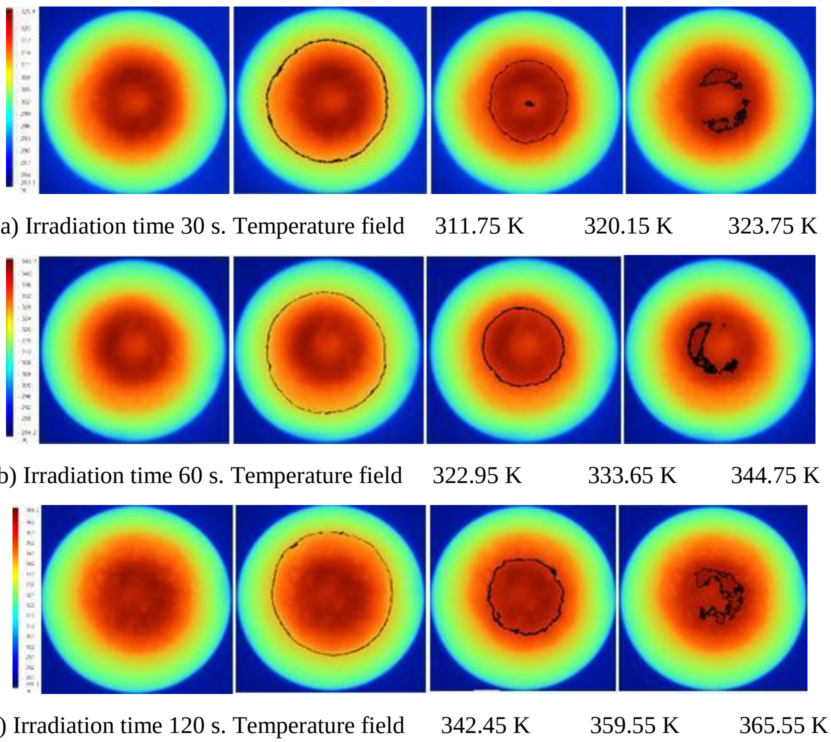
The fly ash used in this study was obtained from a thermal power station of the Fujian province in China. A 30 kg portion of representative sample was divided into 30 portions uniformly. The particle size of the wet fly ash was obtained by a sieve analysis as -74+38 μm. The content of unburned carbon in the wet fly ash was obtained by the *LOI* analysis.

The samples exposed to the atmosphere can absorb moisture. The relative air humidity ranges from 48% to 90%. During this period of time, two samples of wet fly ash were collected and put into a sealed container before the experiments. The moisture contents of two samples were 4.37% and 8.23%, respectively. The wet fly ash had an average *LOI* of 12.65%.

The wet fly ash processed by a microwave oven before the experiments was weighted with an electronic scale. Then, the particles were put on the glass disc uniformly, and the glass disc was heated inside a microwave oven. The experimental conditions in this study were the microwave intensity (60%, 80%, and 100%) and irradiation time (30, 60, and 120 s). The microwave intensity was adjusted by a knob installed on the control panel. The maximal power of the microwave oven was 800 W. The microwave intensity is different from the output power of the microwave oven. The heating intensity is defined by manufacturers. It is only selected by the user and can’t be measured. The heating intensity of 100% indicates that the heating process is continuous. As the heating intensity is smaller than 100%, the heating process is discontinuous. There has been a close relation between the heating intensity and irradiation time. Meanwhile, the irradiation time was monitored by a timer.

Feasibility analysis

The dielectric constant of wet fly ash is larger than that of dry fly ash because of the moisture content. As the wet fly ash is processed by the microwave heating, the dielectric constant will gradually decrease because of the increase in temperature and the decrease in surface moisture. This can lead to reducing of electrical conductivity. The charge transfer can be prevented for the charged particles. It is effective to improve the charged efficiency. Therefore, the higher temperature caused by the microwave heating is conducive to the wet fly ash triboelectrostatic beneficiation. The feasibility of wet fly ash triboelectrostatic beneficiation using microwave heating was analyzed according to the experimental temperature and dielectric constant of particles.



a) Irradiation time 30 s. Temperature field 311.75 K 320.15 K 323.75 K

b) Irradiation time 60 s. Temperature field 322.95 K 333.65 K 344.75 K

c) Irradiation time 120 s. Temperature field 342.45 K 359.55 K 365.55 K

Fig. 1. Isothermal point distribution of temperature field

As the microwave intensity was 100%, the temperature distributions of the fly ash particles were detected by an infrared thermal imager of Ti10 made by FLUKE. The irradiation time was 30, 60, and 120 s. The experimental results analyzed by a software

are seen in Fig. 1. The temperature gradually decreased from inside to outside. The distribution of external isothermal region was circular, and that of central was uneven. The agglomeration of the wet fly ash particles was destroyed due to the vibration of the paricles caused by the microwave heating. The longer the microwave time was, the better the particles dispersion would be.

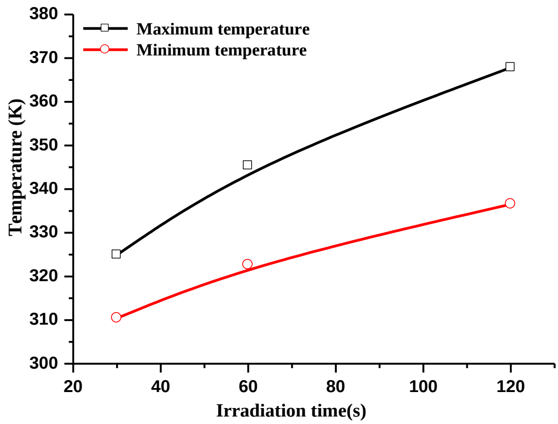


Fig. 2. Relationship between the temperature and irradiation time

A testing system of the dielectric constant is shown in Fig. 3. Two capacitance plates were put inside a metal cover. Three terminals were available for connecting safety ground and measuring instrument. A digital capacitance meter was connected with two electrodes. The measuring device was placed in a thermostat during the experiments. The capacitance was C_0 and C for the plates filled with vacuum and wet fly ash, respectively. The dielectric constant can be calculated as below:

$$\varepsilon = \frac{C}{C_0} \times 100\% \quad (1)$$

The relationship between the dielectric constant and irradiation time is illustrated in Fig. 4. The dielectric constant increased proportionally to the moisture content. The irradiation time of 0 s indicated the unprocessed wet fly ash. The dielectric constants of the particles having moisture contents 2.34%, 5.65%, and 10.23% were 5.29%, 24.02%, and 56.33%, respectively, at the irradiation time 0. The microwave heating reduced the surface moisture of wet the fly ash particles. When the irradiation time was 120 s, the dielectric constant values of the particles decreased to 4.13%, 17.21%, and 39.24%, respectively. The effect of the microwave heating on the dielectric constant values was more obvious with the increase of moisture content. With the increase of the irradiation time, the temperature of the particles increased and the dielectric constant values decreased gradually. Accordingly, the decrease of dielectric constants caused by the microwave heating reduced the electrical conductivity. As the charged particles contacted with each other, it was difficult to realize the transfer of particles surface charge.

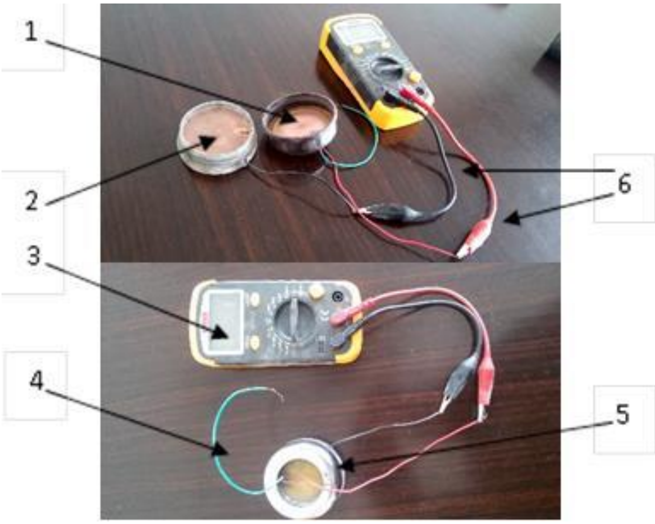


Fig. 3. The testing system of dielectric constant. 1. Positive electrode, 2. Negative electrode, 3. Digital capacitance meter, 4. Ground wire, 5. Metal cover, 6. Wires

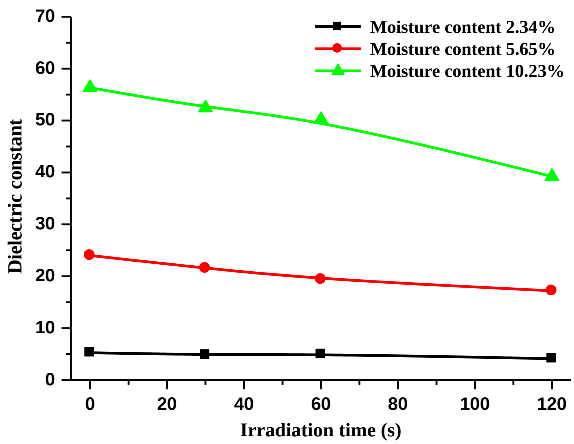


Fig. 4. Relationship between the dielectric constant and irradiation time

Experimental system

An experimental system of fly ash triboelectrostatic beneficiation is demonstrated in Fig. 5. A fan was controlled by a frequency changer in order to obtain the airflow with the flux ranging from 12 to 30 m^3/h. The wet fly ash particles were fed by a vibrator feeder with a controller and sucked into the pipeline. The medium temperature was 283.65 K, and the relative air humidity was 56.5%. The fly ash particles were carried by the airflow produced by the fan. The particles were obtained different charges because of collision and friction inside a tribo-charger. The unburned carbon and the ash carried the opposite charge. The charged particles were injected into the high-voltage static field of 40 KV under the action of the airflow. The voltage was controlled by a power regulator. The motion of carbon and ash particles was in the opposite direction due to the electric field force. While the unburned carbon particles were recycled on the positive plate, the high-quality ash products with low carbon content were collected on the negative plate.

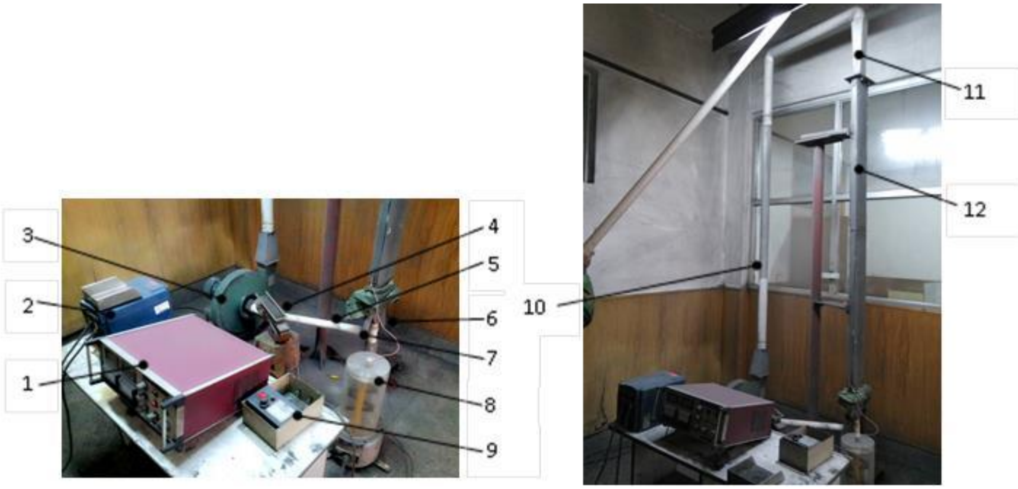


Fig. 5. Experimental system of wet fly ash triboelectrostatic beneficiation. 1. Power regulator, 2. Frequency changer, 3. Fan, 4. Vibrator feeder, 5. Delivery pipe, 6. Positive products 7. Negative products 8. High voltage power supply, 9. Controller of vibrating feeder, 10. Gas-solid mixing pipeline, 11. Tribo-charger, 12. Electric field

Experimental methodology

The efficiency of removal unburned carbon is evaluated by the *LOI* and recycle rate of the unburned carbon (*REC*). The recycling of unburned carbon was estimated by the removal rate of the unburned carbon (*REM*).

The *LOI* is calculated as follows:

$$LOI(\%) = \frac{M_0 - M_1}{M_0} \times 100\% \qquad (2)$$

where M_0 is the mass of unbaked fly ash and crucible, g; M_1 is the mass of baked ash and crucible, g.

The REM and REC are defined as follows:

$$REM\,(\%) = \frac{LOI_s - LOI_-}{LOI_s} \times 100\% \tag{3}$$

$$REC(\%) = \frac{M_+}{M} \times \frac{LOI_+ - LOI_s}{LOI_s} \times 100\% \tag{4}$$

where LOI_S is defined as the *LOI* of fly ash sample before experiment, LOI_+ and LOI_- describes the *LOI* of fly ash obtained from the positive and negative plate, respectively. The mass of fly ash collected from the positive plate is M_+, g. The mass of wet fly ash for each experiment is M_-.

Results and discussion

Influence of microwave intensity

The influence of the microwave intensity on the wet fly ash triboelectrostatic beneficiation was obtained at the irradiation time of 60 s and the moisture content of 4.37%. With the increase of the microwave intensity, the heating time during the same period was longer. The temperature of the particles increased gradually, and it caused reduction of the surface moisture and dielectric constant of the particles. Therefore, it helped the separation of the charged particles. Comparisons of *LOI* with different microwave intensity values are illustrated in Fig. 6.

The LOI_+ increased in proportion to the air flux, whether the fly ash was processed or not, while it was reversed for the negative plate. With the increase of air flux, the difference of LOI_+ between untreated and heated process decreased gradually, while that of LOI_- increased. It suggested that the increase of air flux was conducive to improving the efficiency of fly ash triboelectrostatic beneficiation. The LOI_+ increased from 16.06% to 20.78% for the untreated fly ash, while the LOI_- decreased from 9.68% to 8.48% as the air flux rose from 12 to 30 m^3/h. As the wet fly ash was processed with microwave intensity of 100% and air flux of 30 m^3/h, and the *LOI* of positive and negative plates was 22.07% and 6.98%, respectively. Under the condition of the same air flux, the microwave intensity was proportional to the LOI_+. The results were opposite for the negative plate. As the microwave intensity was increased from 60% to 100%, and air flux was 30 m^3/h, the LOI_+ increased from 20.36% to 22.07%, while the LOI_- decreased from 7.95% to 6.98%.

The comparison of efficiency under different microwave intensity is shown in Fig. 7. The air flux and microwave intensity were in direct proportion to *REM* and *REC*. As the microwave intensity was 60% and air flux of 12 m^3/h, the *REM* and *REC* of wet fly ash processed by the microwave were 31.70% and 18.47%, while those of untreated were 23.48% and 11.59%, respectively. With the increasing of air flux, the difference of *REM* between heated and untreated was more obvious than that of *RE*C. As the air flux ranging from 12 to 30 m^3/h, the *REM* increased from 37.15% to 44.82%, and the *REC* increased from 24.31% to 29.40% with the microwave intensity of 100%. The maximum value of *REM* and *REC* was obtained under the condition of air flux of 30 m^3/h and microwave intensity of 100%.

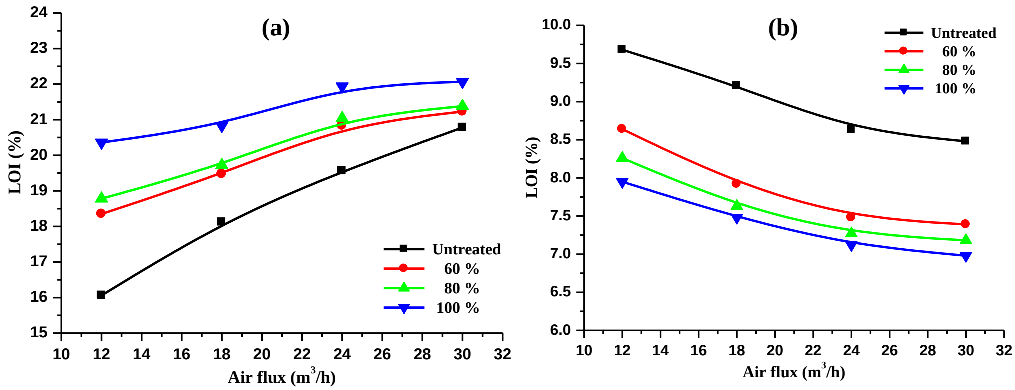


Fig. 6. Comparison of *LOI* under different microwave intensity values.
(a) Positive plate, (b) Negative plate

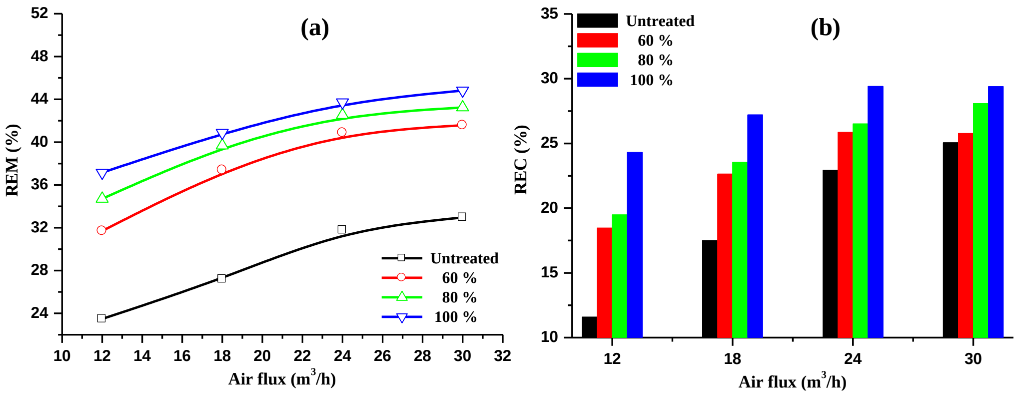


Fig. 7. Comparison of *REM* and *REC* under different microwave intensity. (a) *REM*, (b) *REC*

Influence of irradiation time

The irradiation time had an impact on the dielectric constant. A strong correlation between the irradiation time and temperature of the particles was observed according to the feasibility analysis. The decrease in the surface moisture caused by the microwave heating reduced the dielectric constant and the conductivity of the particles. The separation efficiency of charged particles was improved because the capacity of particles charge storage was enhanced. Figure 8 shows the comparison of *LOI* under the different irradiation time. The microwave intensity was 100%, and the moisture content of materials was 4.37%.

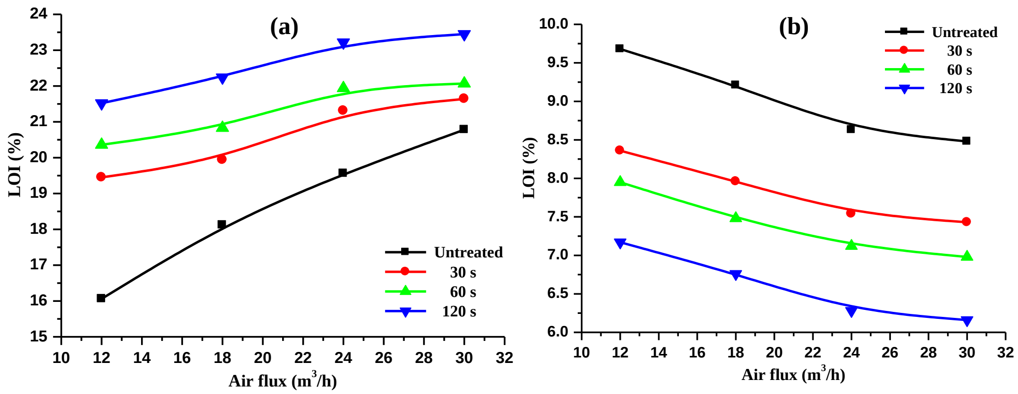


Fig. 8. Comparison of *LOI* under different irradiation time. (a) Positive plate, (b) Negative plate

With the increase of air flux, the difference of LOI_+ between heated and untreated fly ash was decreased gradually, while that of LOI_- was increased slowly. The LOI_+ of heated and untreated was 19.45% and 16.06% as the air flux of 12 m^3/h and the irradiation time of 30s, while the LOI_- was 8.36% and 9.68%, respectively. When the irradiation time was 120 s, the LOI_+ increased from 21.52% to 23.45% as the air flux rose from 12 to 30 m^3/h. The LOI_- decreased from 7.17% to 6.16%. As the irradiation time increased from 30 s to 120 s, the LOI_+ increased from 21.64% to 23.45% with the air flux 30 m^3/h. Meanwhile, the LOI_- decreased from 7.43% to 6.16%. Thus, the irradiation time had an important effect on the triboelectrostatic beneficiation of wet fly ash.

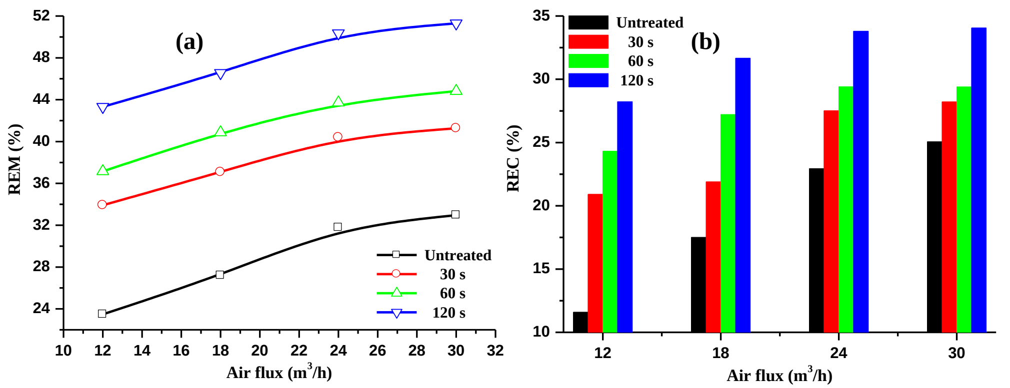


Fig. 9. Comparison of *REM* and *REC* under different irradiation time. (a) *REM*, (b) *REC*

The comparison of *REM* and *REC* under the different irradiation time is shown in Fig. 9. It can be seen there that the efficiency of removal and recovery was improved by the increase of irradiation time. As for the heated and untreated materials, the *REM* difference increased with the increasing of the air flux, and it was reversed to the *REC*.

As the irradiation time of 120 s and the air flux of 12 m^3/h, the *REM* of heated and untreated was 43.32% and 23.48%, while the *REC* was 28.23% and 11.59%. As the air flux rose to 24 m^3/h, the *REM* and *REC* of heated increased to 50.36% and 33.80%, and those of untreated increased to 31.78% and 22.94%, respectively. The longer the irradiation time was, the higher the *REM* and *REC* would be. As the air flux of 30 m^3/h and irradiation time of 120 s, the *REM* and *REC* of heated increased to 51.30% and 34.06%, respectively. The wet fly ash triboelectrostatic beneficiation was realized efficiently.

Influence of moisture content

The higher the moisture content is, the larger the dielectric constant is. When the particles contact each other, it is easy to transfer and cancel the electrical charge for the same and different charged particles. This is not conducive to electrical charging process and particles separation. The microwave heating can improve the separation efficiency according to reduction of the moisture content and dielectric constant of the particles. Two samples with different moisture contents were processed by the microwave heating. The feasibility of improving the efficiency of wet fly ash triboelectrostatic beneficiation was verified by the experimental results. The comparison of *LOI* between two samples with different moisture contents is presented in Fig. 10. The operational conditions were the microwave intensity of 100% and the irradiation time of 120 s.

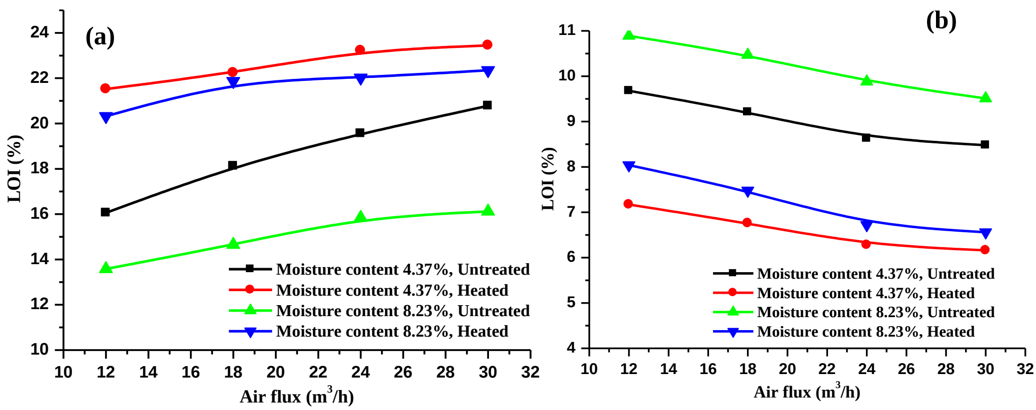


Fig. 10. Comparison of *LOI* for wet fly ash with different moisture content.
(a) Positive plate, (b) Negative plate

The LOI_+ and LOI_- of two samples obviously changed according to the difference of *LOI* between two plates. As for the fly ash with moisture content 4.37% and 8.23%, the LOI_+ of untreated was 20.78% and 16.12% for the air flux of 30 m^3/h. When the wet fly ash with the moisture content of 4.37% was heated, the LOI_+ increased from 20.78% to 23.45%. Moreover, in the case of the wet fly ash with the moisture content 8.23%, the

LOI_+ increased from 16.12% to 22.35% because of the heating process. When the fly ash is processed by microwave heating, the LOI_- of fly ash with moisture content 4.37% decreased from 8.48% to 6.16%, while the moisture content 8.23% decreased from 9.51% to 6.56%.

A comparison of the efficiencies of beneficiation of wet fly ash with different moisture contents is shown in Fig. 11. The *REM* and *REC* increased markedly under the action of microwave heating. At the same operating conditions, the *REM* and *REC* of the sample with the moisture content of 4.37% were higher than those with the moisture content of 8.23%. The difference between two samples decreased gradually with the increasing of air flux. The *REM* of untreated fly ash with moisture content 4.37% increased from 23.49% to 32.96% as the air flux increased from 12 to 30 m^3/h whereas that of heated increased from 43.32% to 51.30%. The *REM* of untreated and heated increased to 24.82% and 48.14% for the wet fly ash with the moisture content 8.23%. As for the two samples with the moisture contents of 4.37% and 8.23%, the *REC* of untreated was 11.59% and 3.73% as the air flux was 12 m^3/h whereas that of heated was 28.23% and 26.55%. When the air flux increased to 30 m^3/h, the *REC* of heated was 8.99% and 20.71% higher than those of unheated. Therefore, the microwave heating can improve the efficiency of wet fly ash triboelectrostatic beneficiation according to the obvious difference between *REM* and *REC*.

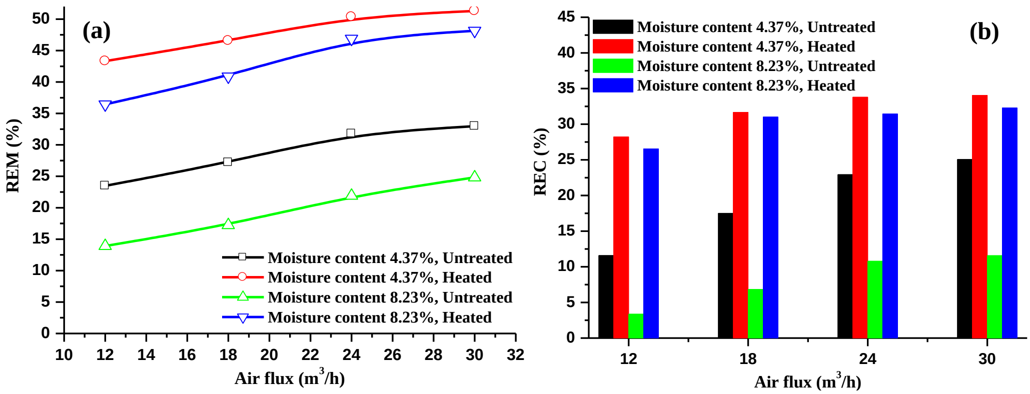


Fig. 11. Comparison of *REM* and *REC* for wet fly ash with different moisture content. (a) *REM*, (b) *REC*

Conclusions

An experimental study was conducted to study the feasibility of improving efficiency of wet fly ash triboelectrostatic beneficiation using microwave heating. The following major conclusions can be drawn from this study.

(1) Microwave heating can increase surface temperature and decrease moisture content of particles. The reduction of dielectric constant and conductivity caused by microwave heating has a positive effect on the electrical charging process. Furthermore, it is difficult to transfer and cancel electrical charges of the particles with the same and

different charges. Therefore, the charged efficiency can be improved by microwave heating.

(2) The difference between the LOI_+ and LOI_- under the same condition was noticeable as the wet fly ash was processed by the microwave heating. With the increase of the air flux, the microwave intensity and irradiation time, the *REM* and *REC* showed a significant increase. The results showed that the microwave heating was an effective method to improve the efficiency of triboelectrostatic beneficiation of wet fly ash. The separation process using the microwave heating can not only obtain the ash-rich products with lower carbon content but also improve the recovery rate of unburned carbon.

(3) According to the experimental study on wet fly ash with different moisture contents, the microwave heating is feasible to improve the efficiency of wet fly ash triboelectrostatic beneficiation. As for the fly ash with moisture content of 4.37% and 8.23%, the *REM* and *REC* increased obviously under the operating conditions at air flux of 30 m^3/h, microwave intensity of 100% and irradiation time of 120 s. Finally, it can be concluded that these results will provide a technical reference for an industrial application of the wet fly ash triboelectrostatic beneficiation.

Acknowledgments

The financial support provided by "the Fundamental Research Funds for the Central Universities" (Project2014QNB12), "China Postdoctoral Science Foundation" (Project2014M560466), "Postdoctoral Science Foundation of Jiangsu Province" (Project1401054B) and "A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions" for this work is gratefully acknowledged.

References

ALI A.Y., BRADSHAW S.M., 2010, *Bonded-particle modelling of microwave-induced damage in ore particles*, Minerals Engineering, 23, 780-790.

ALI A.Y., BRADSHAW S.M., 2011, *Confined particle bed breakage of microwave treated and untreated ores*, Minerals Engineering, 24, 1625-1630.

BAN H., LI, TIAN X., HOWER J.C., SCHAEFER J.L., STENCEL J.M, 1997, *Dry triboelectrostatic beneficiation of fly ash*, Fuel, 76, 801-805.

CANGIALOSI F., NOTARNICOLA M., LIBERTI L., CARAMUSCIO P., BELZ G., GURUPIRA T.Z., STENCEL J.M, 2006, *Significance of surface moisture removal on triboelectrostatic beneficiation of fly ash*, Fuel, 85, 2286-2293.

CANGIALOSI F., NOTARNICOLA M., LIBERTI L., STENCEL J.M, 2008, *The effects of particle concentration and charge exchange on fly ash beneficiation with pneumatic triboelectrostatic separation*, Separation and Purification Technology, 62, 240-248.

CANGIALOSI F., NOTARNICOLA M., LIBERTI L., 2009, *The role of weathering on fly ash charge distribution during triboelectrostatic beneficiation*, Journal of Hazardous Materials, 164, 683-688.

CANGIALOSI F., INTINI G., LIBERTI L., NOTARNICOLA M., DI CANI, F., 2010, *Activated coal fly ash as improved mineral addition in cement and concrete*, 2nd International Conference on Sustainable Construction Materials and Technologies, 1431-1439.

CAO Y.J., LI G.S., LIU J.T., ZHANG H.J., ZHAI X., 2012, *Removal of unburned carbon from fly ash using a cyclonic-static microbubble flotation column*, Journal of the South African Institute of Mining and Metallurgy, 112, 891-896.

HUANG Y., TAKAOKA M., TAKEDA N., 2003, *Removal of unburned carbon from municipal solid waste fly ash by column flotation*, Waste Management, 23, 307-313.

HWANG J. Y., SUN X., LI Z., 2002, *Unburned carbon from fly ash for mercury adsorption: I. Separation and characterization of unburned carbon*, Journal of Minerals and Materials Characterization and Engineering, 1, 39-60.

KATO Y., 2012, *Wet granulation of mixed oxide powders de-nitrated by the microwave heating*, Journal of Nuclear Science and Technology, 49, 999-1009.

KIM J.K, CHO H.C, KIM S.C, 2001, *Removal of unburned carbon from coal fly ash using a pneumatic triboelectrostatic separator*, Journal of Environment Science and Health, Part A, 36, 1709-1724.

Li H.S., Chen Y.H., Wu K.B., Zhang X.X., 2013. *Particle collision during the tribo-electrostatic beneficiation of fly ash based on infrared thermography*. Journal of the South African Institute of Mining and Metallurgy, 113(12), 899-904.

LI H.S., CHEN Y.H., ZHAO Y.M., ZHANG X.X., WU K.B., 2015. *The effect of the cross-sectional shape of friction rods on the triboelectrostatic beneficiation of fly ash*, International Journal of Coal Preparation and Utilization, 35(3), 113-124.

Li H.S., Chen Y.H., Wu K.B., Wu T., Zhang X.X., 2015. *Experimental study on influencing factors of axial clearance for scroll compressor*, International Journal of Refrigeration, 54, 38-44.

LI H.S., ZHANG X.X., CHEN Y.H., 2012, *Collision characteristics of particles in the friction device of triboelectrostatic separator*, Journal of China University of Mining & Technology, 41, 607-612. (In Chinese)

SOONG Y., SCHOFFSTALL M.R., LINK T.A., 2001, *Triboelectrostatic beneficiation of fly ash*, Fuel, 80, 879–884.